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14. ABSTRACT
Several experiments to measure the burial of seafloor mines by scour and fill have been conducted at the Woods Hole Oceanographic Institution Martha's Vineyard Coastal Observatory (MVCO). Two sets of mine scour burial experiments were conducted during the winters of 2001-02 and 2002-03 with a single optically-instrumented mine in the field of view of a rotary sidescan sonar, and sixteen mines were deployed from October 2003 to April of 2004, along with several systems to image mine behavior and to characterize bedform and oceanographic processes. The sedimentary environment at MVCO consists of a series of rippled scour depressions, which are large-scale bedforms with alternating areas of coarse and fine sand. In fine sand the sonar imagery of the mines reveal that large scour pits form around the mines during energetic wave events. The mines fall into their own scour pits, aligning with the dominant wave crests and become level with the ambient seafloor after one or two wave events. Infilling of the scour pits appears to be a slower and more variable process and often takes several months before the scour pits infill. The coarse sand supports large wave orbital ripples with wavelengths of 50 cm to 150 cm and heights of 10 to 20 cm. In the coarse sand the mines were observed to bury until the exposed cross-section was approximately the same size as the large wave orbital ripples.

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Mine burial experiments at the Martha's Vineyard Coastal Observatory

Peter Traykovski, Michael D. Richardson, John A. Goff, Larry Mayer, Roy Wilkens, and Brendan Gotowoka

Abstract: Several experiments to measure the burial of seafloor mines by scour and fill have been conducted at the Woods Hole Oceanographic Institution Martha's Vineyard Coastal Observatory (MVCO). Two sets of mine scour burial experiments were conducted during the winters of 2001-02 and 2002-03 with a single optically-instrumented mine in the field of view of a rotary sidescan sonar, and sixteen mines were deployed from October 2003 to April of 2004, along with several systems to image mine behavior and to characterize bedform and oceanographic processes. The sedimentary environment at MVCO consists of a series of rippled scour depressions, which are large-scale bedforms with alternating areas of coarse and fine sand. In fine sand the sonar imagery of the mines reveal that large scour pits form around the mines during energetic wave events. The mines fall into their own scour pits, aligning with the dominant wave crests and become level with the ambient seafloor after one or two wave events. Infilling of the scour pits appears to be a slower and more variable process and often takes several months before the scour pits infill. The coarse sand supports large wave orbital ripples with wavelengths of 50 cm to 150 cm and heights of 10 to 20 cm. In the coarse sand the mines were observed to bury until the exposed cross-section was approximately the same size as the large wave orbital ripples.

Introduction: In order to improve our ability to predict burial of seafloor mines the U.S. Navy Office of Naval Research (ONR) sponsored a mine burial experimental program at the Martha's Vineyard Coastal Observatory (MVCO).

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Two sets of mine scour burial experiments were conducted during the winters of 2001-02 and 2002-03 with a single optically-instrumented mine and a rotary sidescan sonar to monitor mine behavior during storms events and to test wave-induced scour burial models (Fig. 1) [1]. These experiments were preparatory for a larger ONR experiment conducted during the winter of 2003-04. Several site characterization cruises were conducted with high-resolution bathymetry and sidescan sonar mapping, a chirp sonar seismic survey, surface grain size analysis at a large number of stations, and 1 to 3 m vibracores at a smaller number of stations. During the major experimental program sixteen mines were deployed from October 2003 to April of 2004, along with several bottom-mounted systems to image mine behavior and to characterize bedform and oceanographic processes.

Oceanographic Conditions: The oceanographic forcing for sediment transport and mine burial at MVCO is dominated by waves from southerly directions (Fig. 2d). Waves from the northeast and east are blocked by the shallow (2 to 3 m depth) Wasque shoals located to the east of the study site. Wave heights are typically largest from October to March, with occasional large wave events in the late summer from passing tropical storms or hurricanes (Fig. 1). The largest storms observed over the three measurement years had significant wave heights of 3 to 4 m and occurred approximately 5 to 10 times per year. Storms with significant wave heights between 2 and 3 m occurred between 10 and 20 times per year. Peak wave periods during storms range from 8 seconds to 13 seconds. The near-bed wave orbital velocities generated by the largest wave events at the MVCO site in 11 to 12 m water depth reach r.m.s. values of 50 to 70 cm/s. Bottom currents are typically tidal with peak velocities of 10 to 20 cm/s at 1 meter above the bed. Storm generated bottom currents can reach 30 to 40 cm/s; however, not all large wave events have associated strong currents. Since waves produce a larger shear stress than mean currents with similar velocities, wave orbital velocities dominated scour around the mines.

Seabed Characteristics: The seafloor at MVCO consists of a series of features known as rippled scour depressions or sorted bedforms [2, 3]. These are shore perpendicular swaths of coarse sand (250 to 1000 μm) with widths ranging from 10's to 100's of meters and lengths of one to several kilometers (Fig. 2a).

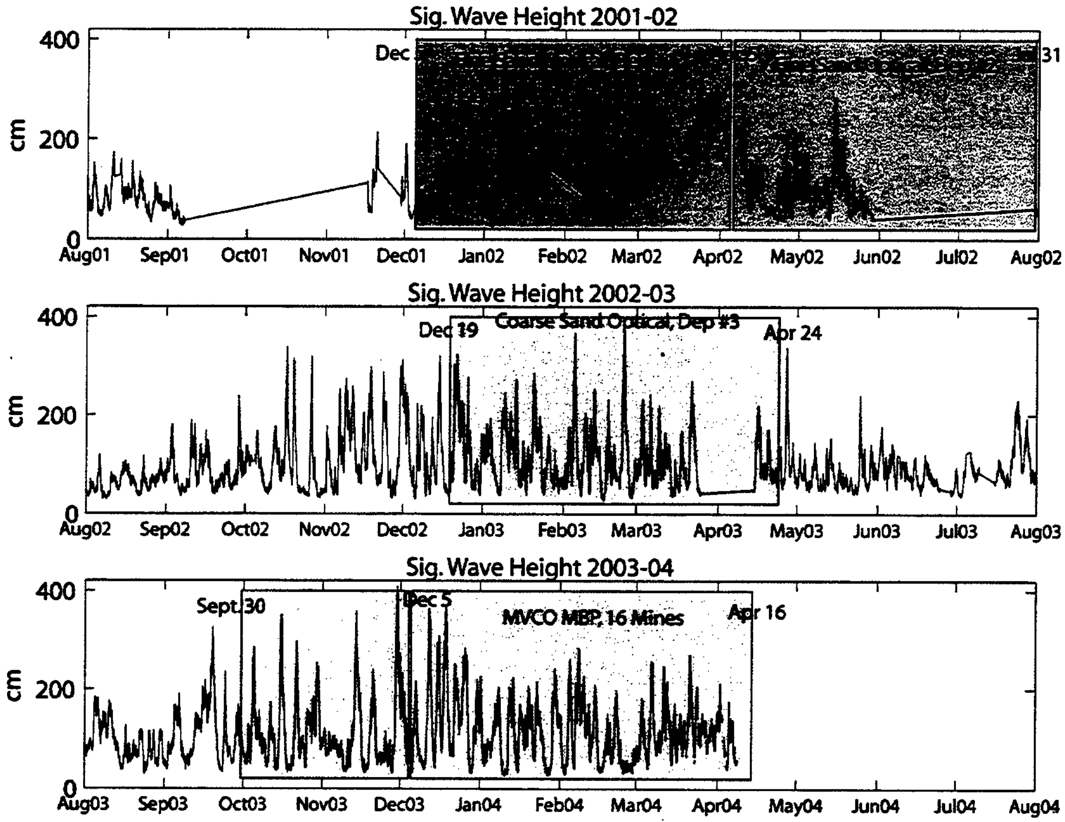

Fig. 1. Time series of significant wave heights from the MVCO node for 2001 through 2004. The gray shaded regions indicate the mine deployments.

. A layer of fine sands (90 to 175 μm) inhabit the regions between the coarse sand zones with thickness ranging from ~15 to 50 cm. Coarse sands underlie the fine sands, and a gravelly layer is often present at this transition. The gravel layer is also present ~10-50 cm below the surface in the coarse sand zones. In the vicinity of the mine burial experiment, the transition from fine to coarse sand is marked bathymetrically by a drop of ~30-50 cm. The interior of the coarse sand zones are mounded, sometimes approaching the same height as the surrounding fine sands, and with an overall tilt upward to the east. This bathymetric expression is not consistent throughout the survey area, however [3].

Small Scale Bedforms: The coarse sand supports wave orbital-scale bedforms with wavelengths of 50 to 125 cm and heights of 5 to 20 cm (Fig. 2b) [4]. As the name implies these ripples have wavelengths and heights that scale with wave orbital diameter. These bedforms have been observed by rotary sidescan sonars to migrate in response to wave velocity skewness. This generally results in onshore migration at rates of approximately one wavelength per day. The wave orbital ripples are very long crested features; however, during the most energetic conditions, with Shields numbers of 0.2, the coarse sand bedforms become irregular and migrate at rates of 2 to 3 wavelengths per day. In the fine sand, during small wave events anorbital ripples of wavelengths 10 to 20 cm and heights 1 to 2 cm were present (Fig. 2c). During large wave events (with Shields numbers of 0.5 to 0.7) these small ripples were washed out. The high-resolution bathymetric surveys also identified medium-scale low relief bedforms in the fine sand. These features have length scales of 3 to 5 meters and heights of 10 to 15 cm and have an irregular geometry. The migration or geometric evolution of these features may play an important role in infilling fine sand scour pits around mines located in fine sand sediments. It is not known if they persist through high-energy events as the slopes associated with these features are too low to be imaged by the rotary fanbeam sonars. However; the high-resolution bathymetric data images show they are transient, as they appear in some surveys, but not in others taken several months apart.

Mine Deployments: Ten instrumented and six passive dummy mines were deployed in both the fine and coarse sand at MVCO during the winter of 2003-2004 mine burial experiments. The mines were deployed in late September of 2003, and several mines were repositioned in early December of 2003 (Fig. 1). In April of 2004 most of the mines were recovered; however, some of the more deeply buried mines were not located because of poor visibility and otherwise difficult diving conditions. High-resolution bathymetric surveys, capable of resolving mines at the

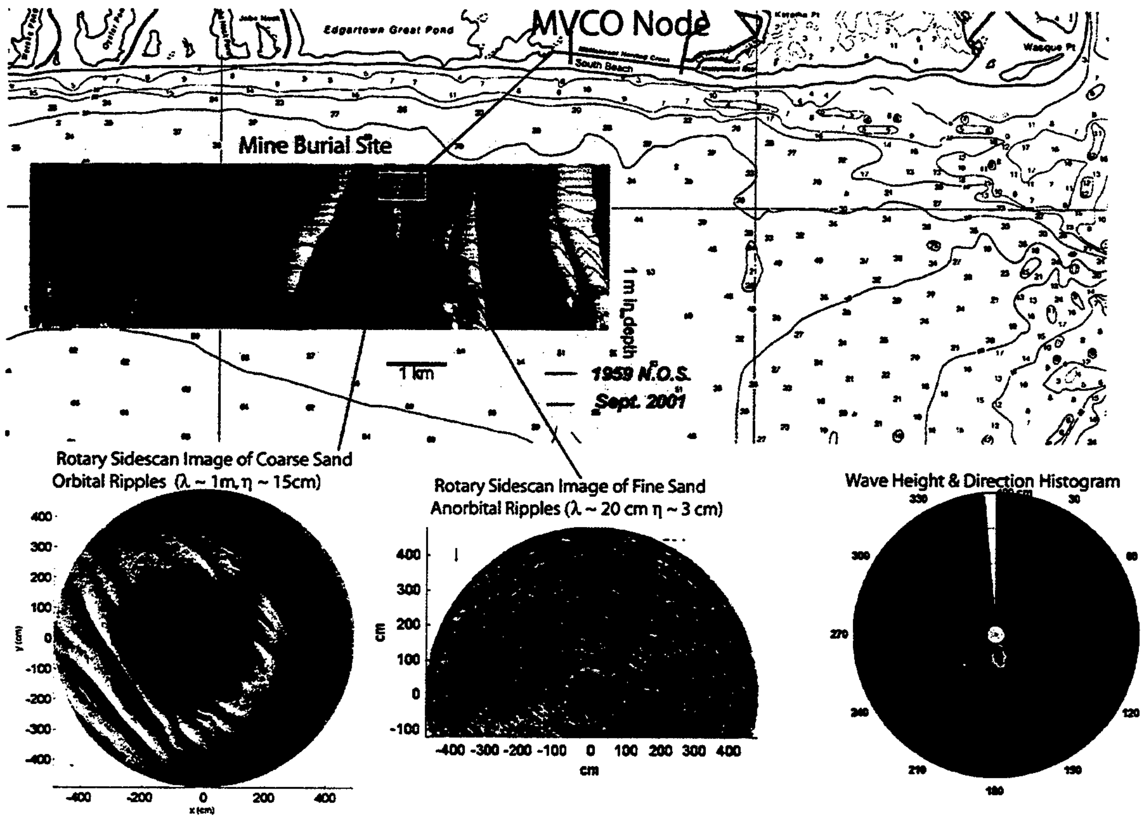

Fig. 2. a) Sidescan sonar data inset into a nautical chart of the South Eastern Corner of Martha's Vineyard. The high backscatter areas (light) are coarse sand rippled scour depressions and the low backscatter areas are finer sand. b) A rotary sidescan sonar image in a rippled scour depression showing large wave orbital ripples. c) In the fine sand smaller an-orbital ripples are present. d) A histogram of wave heights from the three years of data indicates the largest waves approach from the south and southwesterly directions. The wave orbital ripples align perpendicular to the waves and the rippled scour depressions are approximately parallel to the waves.

seafloor, were conducted immediately following the deployment, before the repositioning, and before the final recovery. Four cylindrical mines (AIMs) had acoustic sensors to measure their own scour pit and surface area burial [5]. Pressure sensors in the acoustically instrumented mines estimated significant wave heights and periods and were used to measure burial relative to a fixed height above the seafloor.

Six other cylindrical mines had optical sensors to measure surface area burial. All of the instrumented mines had roll, and pitch sensors to determine the orientation of the mine as it buried, but only the acoustic mines had heading sensors. The ten cylindrical mines were approximately 50 cm in diameter and had lengths of 1.5 to 2 m. The remaining six inert mines had varied non-cylindrical geometries and had no internal instrumentation.

The mines were deployed in three groups to characterize scour burial in both the coarse and fine sand. (Fig. 3). Within each group mines were placed on a grid with approximately 25 m spacing between mines to prevent mines from influencing each other. Two acoustic instrumented mines (AIMs) were deployed in fine sand within 30m of the MVCO 12 m depth node which allowed Ethernet communications without in-line amplifiers and provided power. Two optically instrumented mines were also deployed near the node. Based on the core data, the fine sand layer near the node was relatively thin (approximately 20 to 30 cm), therefore a second group of six mines was deployed in a region with a thicker layer (40 to 50 cm) of fine sand located approximately 300 m to the west of the node. The remaining four mines, two of which were AIMs, were deployed in a swath of coarse sand 100m east of the node.

A rotary sidescan sonar and a two-axis pencil beam sonar were mounted adjacent to the AIM located near the MVCO node. The sonars imaged the scour pit formation around the mine and any interaction of bedforms with the scour pit. This system was connected to the MVCO node to allow real time data communication and to provide power. The rotary sidescan sonar produces an image of the scour pit based on acoustic intensity from seafloor slope relative to the transducer head, but does not give a quantitative elevation measurement of the scour pit and mine surface. The two-axis pencil beam sonar takes longer to image the mine as it must step through 180 degrees on each axis of rotation, but produces a quantitative microbathymetric (cm scale

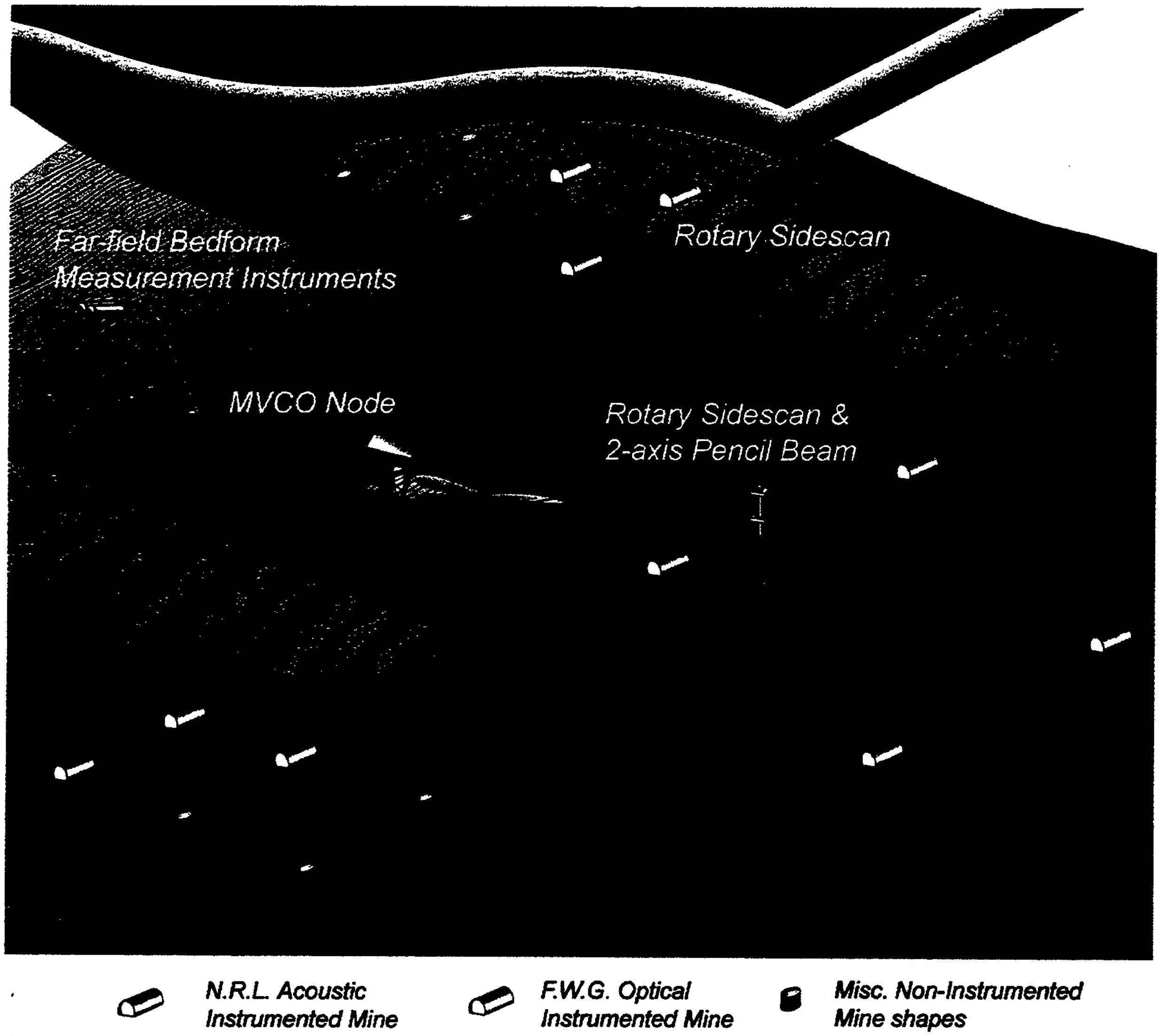

Fig. 3. Schematic of the MVCO node area showing the fine sand near the node and coarse rippled sand approximately 100m from the node. The layout of acoustic and optical instrumented mines relative to the imaging sonars is also shown.

resolution) measurement of the scour pit and the mines position in the scour pit. A rotary sidescan sonar was also deployed near an AIM in the coarse sand and was cabled to the node. Three additional autonomous rotary fan-beam sonars were also deployed near mines by University of South Florida Investigator Peter Howd, two in fine sand to the west and one in the coarse sand to the east of the node.

Results: In the preliminary deployments (winter 2001-02), an optical mine deployed on fine sand buried completely in 70 days, during five storms with significant wave heights over 3 m. Divers observed that the top of this mine was located 10 cm under the sand-water interface at recovery. A second deployment of the same optical mine on fine sand during the winter of 2001-02 resulted in 60% surface area burial during three storms with significant wave heights over two meters. Rotary sonar images showed the formation of scour pits, the mine collapsing into the scour pits, and subsequent infilling, which partially or fully buried the mines. In the winter of 2002-03 the optical mine was also deployed in coarse sand and buried during the first 3 m wave event so that approximately 25 cm was exposed. The ripples in the coarse sand were 10-15 cm high thus the percent surface area buried varied as ripples migrated past the mine. During the larger experiments conducted during 2003-04, two AIMs deployed at the coarse sand site buried so that approximately 10 to 20 cm was exposed, depending the position of the ripples relative to the mine. This burial is, similar to burial that occurred during the 2002-03 experiment. In both experiments the mines rotated so that they were aligned perpendicular to the dominant wave direction, which was also parallel to the ripple crests (Fig. 4).

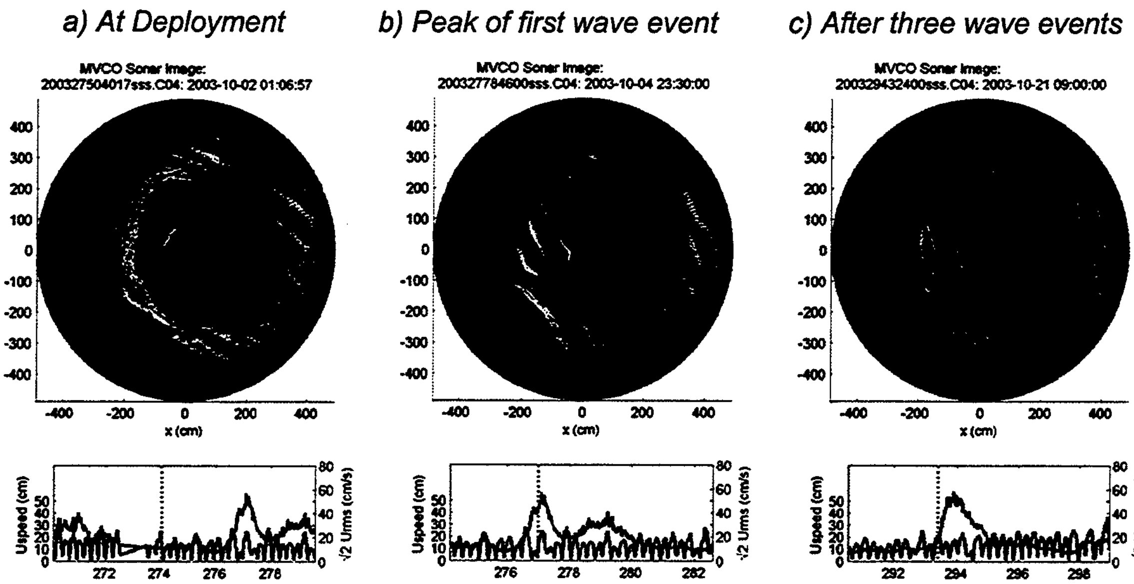

Fig. 4. Three rotary sidescan images of an instrumented mine in coarse sand with r.m.s. wave (red) and current (blue) velocities shown below. The mine is visible in the lower left of the sonar image. At the beginning of the deployment (a) it is fully exposed as indicated by the long acoustic shadow. b) During the peak of the first storm the mine rotates to align parallel to the ripples, which are also parallel to the crests of the incoming waves. c) After three storms the mine is partially buried so that it's shadow is approximately the same length as the shadow of the large ripples.

A large well-defined scour pit was not visible around the mines in the coarse sand rotary sonar images; however, an area of small-scale irregular roughness was observed near the corners of the mines. We postulate that in the coarse sand the mines bury until they present roughly the same hydrodynamic roughness as nearby orbital scale bedforms, heights of 10 to 15 cm in our case. At this stage mines do not produce more turbulence than the bedform themselves and ripples simply migrate past the mines leaving them partially buried.

In the 2003-04 deployments images from the rotary and two-axis pencil beam sonar of an AIM mine located in fine sand showed formation of a large scour pit around the instrumented mine. The mine fell into its own scour pit so that the top of the mine was approximately level with the ambient seafloor after five storms with significant wave heights in excess of 3 m. At the time of the repositioning cruise in December 2003 the infilling events had not resulted in complete burial of the surface of the mine. However at the time of the final recovery in April 2004,all of the cylindrical mines located in fine sand were completely buried as the scour pits had infilled.

The 2-axis sonar system deployed in the 2003-2004 deployments provides additional insights into the scour and infilling processes in fine sand. The system was mounted on a 2 inch diameter pole jetted approximately 5 feet into the seafloor. This mounting technique provides minimal disturbance to the seafloor, and was adequate to support the low profile rotary sidescan sonar system. However, with the extra weight and hydrodynamic drag caused by the 2-axis sonar, the pole tilted during the first few storms and then eventually fell over. In post processing of the data the tilt can be removed since the position of the mine is known from its own internal sensors. For this paper a single storm where the instrument did not tilt will is examined. Unlike the rotary sidescan sonar, which only provides an image of backscattered intensity, the 2-axis sonar provides both a bathymetric map and a map of the backscatter strength of the seafloor surface (Fig. 5). The backscatter data shown in Fig. 5 has been calibrated to compensate for spherical spreading and attenuation with the instruments time variable gain, but has not been corrected for the local angle with the seafloor surface or mine surface.

At the beginning of the storm on Oct 21 -23, 2003 (Fig. 5a) the mine was surrounded by a 4 m diameter scour pit with a maximum depth of 30 cm below the ambient seafloor level. The mine had previously fallen into this scour pit so that the top of the mine was 5 to 10 cm above the ambient seafloor on one end. The backscattered intensity is relatively high on the seafloor surrounding the scour pit, but is low in the scour pit. Note that backscattered intensity is low on both the side of the scour pit angled toward the sonar and the side angled away from the sonar. Thus the dependence on local angle is much weaker than the dependence on location relative to the scour pit. . We postulate that this difference in backscatter is due to the scour pit infilling with finer sediment than the surrounding seafloor, and that the finer sediment has lower backscatter strength.. At the peak of the storm, with 3 m wave height and 40 cm/s r.m.s wave orbital velocities (Fig. 5b), the depth of the scout pit i increased to 40 to 50 cm deep relative to the

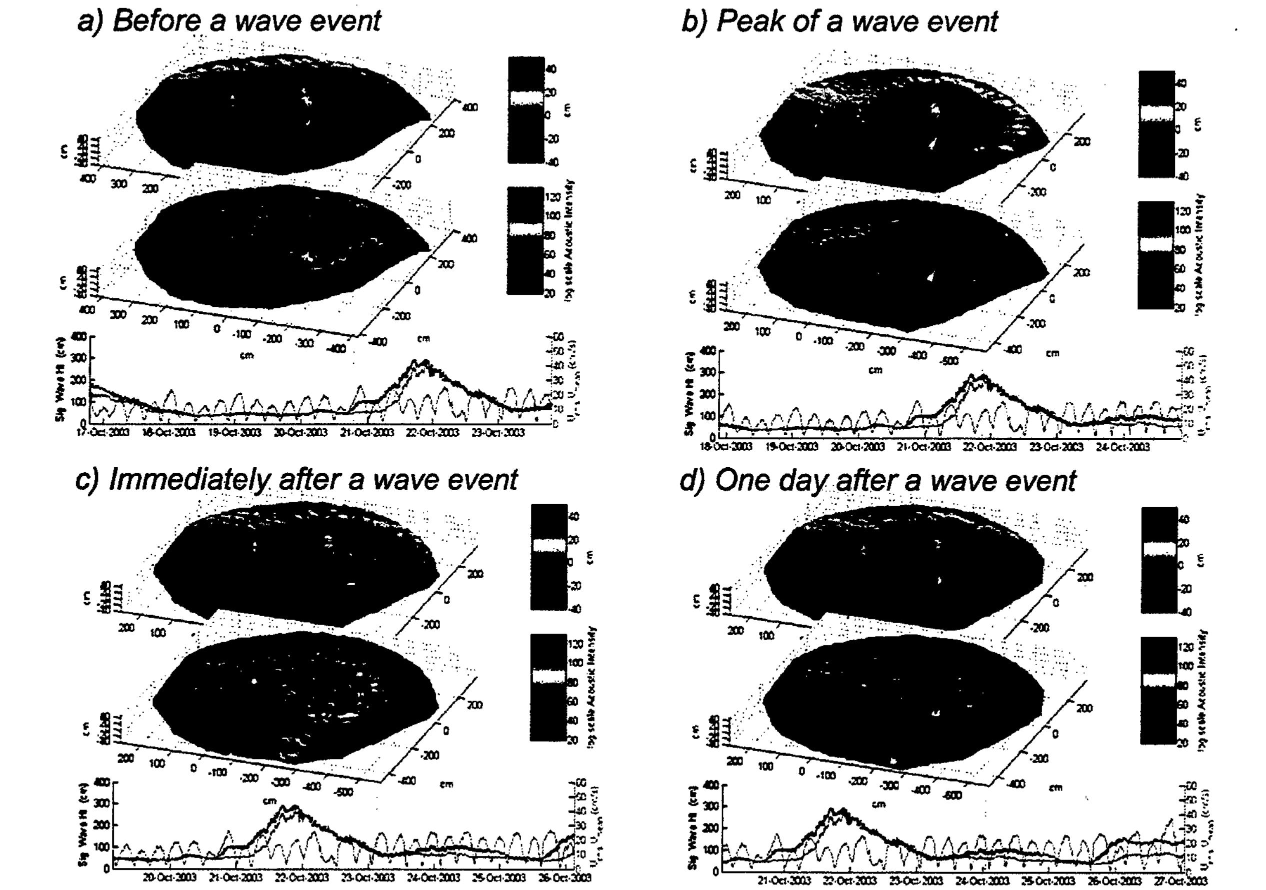

Fig. 5. Four data sets taken at the beginning, peak, and two days after a wave event from the 2-axis rotary pencil beam system. The upper image in each panel shows the small scale bathymetry associated with the mine and it's scour pit. The color indicates height above a mean reference surface. The lower image in each panel shows backscattered intensity draped over the bathymetric surface. The color represents backscattered intensity. As the wave event progresses the development and infilling of the scour pit can be clearly seen in the bathymetry data. The backscatter images reveal surfaces exposed by scour have relatively high backscatter and infilled surfaces have much lower backscatter

ambient seafloor while maintaining approximately the same diameter (Fig. 5b). The ambient seafloor elevation increased slightly so the mine is approximately level or a few centimeters proud of the ambient seafloor. The change in backscatter strengths in the scour pit dramatically increased compared to before the storm (5a verse 5b). During the peak of the storm the backscatter is high both in the scour pit and on the surrounding seafloor. We postulate that the infilled fine sediment was removed in the scour process and that coarser, higher backscatter, sediment remains. As the storm subsides, during slack tides, the scour pit becomes infilled (Fig. 5c) so that it is 10 to 30 cm deep relative to the ambient seafloor. The infilled material has lower backscatter and is occasionally almost acoustically transparent, thus there is a high variance in the bottom location estimate, as the threshold detector does not perform well with the low and variable backscatter surface. One day after the end of the storm, and after several days of spring tidal velocities (30 cm/s), the fine grained material that has infilled the scour pit was eroded near the ends of the mine and only two lobes of fine sediment remain near the middle of the mine (Fig. 5d). This is evident from the low backscatter near the middle of the mine and high backscatter near the ends of the mine. This process repeats itself in subsequent storms with slightly more infilled material preserved after each storm, so that 6 months after the initial deployments the surface of the cylindrical mines in fine sand are completely buried and the top of the mines were at or below the level of the ambient seafloor.

Conclusions: Based on 12 deployments of cylindrical mines in fine sand and 4 deployments in coarse sand at the Martha's Vineyard Observatory, we can summarize the data as follows: In coarse sand, where bedload is the dominant sediment transport mode, and large wave orbital ripples are present, mines typically do not bury completely. The mines bury until they present roughly the same hydrodynamic roughness as the orbital scale bedforms present in coarse sand (10 to 15 cm). At this stage mines do not produce more turbulence than the bedform themselves and ripples simply migrate past the mines leaving them partially buried. In fine sand large scour pits form relatively quickly during energetic storms. These scour pits allow the mines to sink until the top of the mine is approximately level with the ambient seafloor. Infilling, often with finer sediment, then occurs over a longer time scale, with periods of complete infill and periods of partial exposure, until the infilled sediment becomes resistant enough to resuspension that the mines no longer become exposed.

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